PREDICTION OF AIRBLAST PRESSURES FROM EXPLOSIONS IN UNDERGROUND MAGAZINES

USING BLASTX, VERSION 3

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The WES BLASTX code was recently revised (Version 3) to predict the airblast and thermal effects of large explosions in small rooms. This paper compares the results of internal gas pressure\ external shock calculations against measured data from tests in large-scale and small-scale underground magazines. Comparison of calculated and measured internal blast pressures indicate that the code tends to wider-predict internal gas pressure. In most cases, however, the BLASTX3 code provides good predictions of the general level of internal and external airblast effects.

INTRODUCTION AND BACKGROUND

The U.S. Army Engineer Waterways Experiment Station (WES) has actively supported development, of the BLASTIN/BLASTX family of fast-running analytical, semi-empirical computer codes to predict internal and external blast effects from explosions inside or near structures. The early BLASTIN family of codes treated the combined shock wave (including multiple reflections) and explosive gas pressure from the detonation of conventional high explosives in a closed rectangular box-shaped room. The early versions computed the blast effects from the detonation of a small charge in a large room (small chamber loading density), and therefore could not compute blast effects from the accidental detonation of a large quantity of ammunition in an underground storage magazine. Later improvements, culminating in BLASTX, Version 3 (BLASTX3), have expanded the capabilities of the code to include multiple, many-walled rooms and multiple explosive charges.

Analysis of recent WES small-scale test data (from the Joint U.S./Korea (ROK) R&D Program for New Underground Ammunition Storage Technologies), and results from hydrocode calculations (RAGE and SHARC) indicated that, for large loading densities, burning and venting' of detonation products are the principal sources of internal and external blast from underground magazines, and that secondary burning of oxygen-deficient explosives is an important contributor to these pressures. As a result of this analysis, the analytical model within BLASTX was modified to include smaller time steps in the gas venting calculations in order to handle the rapid mass and energy flows associated with large confined detonations. Thus, Version 3 of the BLASTX code (BLASTX3) was specifically developed for computation of blast effects from accidental detonations in underground ammunition storage magazines.

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COMPUTATIONAL MODELS

Airblast data are available from a limited number of large-scale tests which simulated accidental explosions in underground magazines. These include the 1988 KLOTZ Club test at China Lake, CA, the Camp Stanley design validation test, and most recently, the Linchburg Mine experiments of the Joint U.S./ROK program. These limited data are augmented by an extensive series of small-scale experiments conducted by WES under the Joint U.S./ROK program. Computer simulations of seven WES small-scale models and the three large-scale experiments mentioned earlier will be presented and discussed in this paper.

Two model detonation chambers were used for the WES small-scale magazine experiments. The larger chamber (Figure 1) had an internal diameter of 0.508 m, and was used for testing at loading densities of 1.67, 3.33, and 5.00 kg/m^3. The inside diameter of the smaller detonation chamber was 0.146 m. This chamber was used for testing at loading densities of 1.0, 5.0, 15.0, and 42.0 (one detonation) kg/m^3. Both detonation chambers were 1.8 m long. The exit tunnels were modeled using heavy-walled steel pipe, 24.3 cm in diameter for the large chamber, and 14.6 cm in diameter for the smaller chamber.

Britt (1994) suggests that BLASTX would most efficiently model rooms with an aspect (length-to-width) ratio of 3:1 close-in to the detonation, in order to investigate blast effects in underground munitions storage magazine systems. Thus, the larger detonation chamber was modeled as a single cylindrical room while the smaller chamber was divided into six cylindrical cells. The exit tunnels were divided into cylindrical cells with aspect ratios as close to 3:1 as possible for computational modeling.

BLASTX models explosive charges as spherical sources, and can include multiple charges in multiple rooms. The explosive charges in the physical models were long (22.4 cm), rectangular parallelepipeds. In the larger small-scale detonation chamber, the charge was modeled as a single spherical source, positioned at the center of the chamber. The explosive charge used in the small detonation chamber was cylindrical and was simulated by two spherical sources placed in the cells on either side of the center of the chamber.

RESULTS FOR SMALL-SCALE MODELS

The small-scale model magazine layout shown in Figure 1 (Test 1/9) is termed a "shotgun" design. A comparison of the peak measured data to the BLASTX computed gas pressure (internal) and shock (external) for a test with a 5.0 kg/m^3 loading density is shown in Figure 2. The measured internal pressures were slightly higher than the calculated gas pressures. However, the comparison show very good correlation between measured and computed external pressures.

A similar shot-gun model magazine is shown in Figure 3. The access tunnel cross-sectional of this model is 2.8 time larger than the previous model and the length has been doubled. As shown in Figure 4, the BLASTX3 code slightly under-predicted the internal pressures, but predicts free-field pressures very well.

The layout of a small-scale model magazine with an "in-line" expansion chamber is shown in Figure 5. The expansion chamber volume is equal to that of the detonation chamber in this model. Tests were conducted at three different loading densities, 1.67, 3.33 and 5.00 kg/m^3. Figure 6 presents a comparison between the measured pressures and the BLASTX3 predictions for a loading density of 1.67 kg/m^3. The previous comparisons of measured data to BLASTX3 predictions for the free-field did not extend to the Inhabited Building Distance (IBD), which is defined by safety regulations as the 6.2 kPa overpressure level. As shown in Figure 6, the computation slightly over-predicts the IBD for this model. Similar comparisons for other detonation experiments with this model magazine are shown in Figures ~ and 8 (loading density of 3.33 and 5.0 kg/m^3, respectively). These plots indicate a trend for the BLASTX3-predicted IBD to fall below the measured data as the chamber loading density is increased.

The layout for a small-scale magazine with a transverse expansion chamber and dual exits (Test 2/82) is shown in Figure 9. The expansion chamber volume was 70 percent of that of the detonation chamber. A single test was performed on this model configuration at a chamber loading of 5.0 kg/m^3. A comparison between the measured pressures and the BLASTX3-calculated values is shown in Figure 10. Although there is some scatter of the measured peak data, the calculated and measured values are reasonably close, especially in the region near the IBD.

Figure 11 shows the model configuration for Test 2/106, which was a "shotgun" magazine design with a constriction between the detonation chamber and the exit tunnel. The constriction opening was only 10 percent of the tunnel diameter. The measured data from this test exhibits considerable scatter about the calculated peak gas pressure values. An average curve through the measured data would, however, cross the IBD very close to the BLASTX3 -calculated IBD.

The configuration for model Test 2/113 is shown in Figure 13. The smaller detonation chamber was used for this model to provide higher loading densities. Test 2/113 was conducted at a chamber loading density of 15.0 kg/m^3. As shown in Figure 14, the measured peak overpressure values were consistently larger than the calculated gas pressures.

A steel plate was bolted over one of the two tunnel exits. Thus, the model magazine used for Test 2/117 had the same volume as that used for Test 2/113, but the gas pressure had only one exit. Comparison of the measured and predicted pressures is presented in Figure 16. While the measured internal pressures were slightly higher than the calculated values, the computed free-field pressures agree quite well with measured data at the IBD.

RESULTS FOR LARGE-SCALE TESTS

The test layout for the KLOTZ Club's 1988 shallow underground magazine test at China Lake, CA, is shown in Figure 17. The chamber cover thickness was 9.4 m, which was not sufficient to prevent rupture of the cover. As shown in Figure 18, the BLASTX3-calculated

gas pressures for this test were consistently greater than the measured data. This difference is attributed to gas venting through the ruptured overburden.

The longitudinal tunnel cross-section for the 1/3-scale Camp Stanley Munitions Storage Facility, Concept Validation Test is given in Figure 19. Three charges were detonated in Chamber B; 10.7, 57.8, and 336 kg of Composition B explosive. Since the chambers opened directly into the main drift, we can only estimate the nominal chamber loading densities. The densities were assumed to be 0.35, 1.91, and 11.1 kg/m^3 (NEW).

A comparison of the computational results and measured data from Test No. 1 is presented in Figure 20. BLASTX3 predicts peak values larger than the measured data by a factor of 2 to 4, for this test geometry. Similar data plots for Tests No. 2 and 4 are shown in Figure 21 and 22, respectively. A good match between calculated and measured data is indicated in these graphs.

The layout of the Intermediate-Scale test facility at the Linchburg Mine for the Joint US/ROK R&D Program is shown in Figure 23. The tests at this site were all conducted in Chamber No. 4 with cast Composition B charges. The explosives were placed on a platform at the center of the chamber. Chamber loading densities were 1.1, 5.5, 14.6, and 37.3 kg/m^3.

Comparisons of computed gas pressures with the measured data from Test No.2 (loading density of 1.1 kg/m^3) is presented in Figure 24. BLASTX3 under-predicts internal pressures in the storage chamber and access tunnel, and over-predicts pressures in the main drift and free-field. Similar comparisons from Tests 3, 5, and 6 are presented in Figures 25, 26, and 27, respectively. The over-prediction in the free-field is attributed to the over-prediction of internal pressures in the main drift. The internal volume of the main drift was measured by shadow photography techniques, and probably underestimated the actual volume slightly.

CONCLUSIONS

Airblast peak pressures calculated by the BLASTX3 computer model have been compared with test data for a variety of underground magazine designs, at both large and small-scale. The small-scale results are more consistent, primarily, it is presumed, because these models were fabricated from cylindrical pipe of uniform cross-section. The volumes and dimensions of these models are easily determined. The calculations for the small-scale models provided a good prediction of the peak measured internal and external pressures.

For the large-scale underground magazine, BLASTX3 generally produced values that were significantly higher than those measured, particularly at greater distances in the tunnels and in the free-field. The over-prediction of external pressures for the KLOTZ 1988 China Lake experiment is attributed to early venting of the detonation gases through rupture of the chamber overburden. Good predictions were made of the peak data from the 1/3-scale Camp Stanley validation experiments. Calculations for the intermediate-scale underground magazine complex of the U.S./ROK program yields pressures higher than the measured data in the main drift and free-field. The over-prediction may have been due to under-estimating

the volumes of the long tunnel. BLASTX3 has been shown, however, to provide a highly useful tool for prediction of the blast environment in underground ammunition storage facilities, particularly since the errors from the calculations reported here were always safety-conservative. 6

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J. R. Britt, and M. G. Lunsden; " Internal Blast and Thermal Environment From Internal and External Explosions: A User's Guide For The BLASTX Code, Version 3.0," SAIC 405-94-2, May 1994, Science Applications International Corporation, Theoretical Physics Division, San Diego, CA.

Figure 1. Small-scale shot-gun magazine model; Series 1, Test 9 layout, chamber loading density of 5.0 kg/m^3.

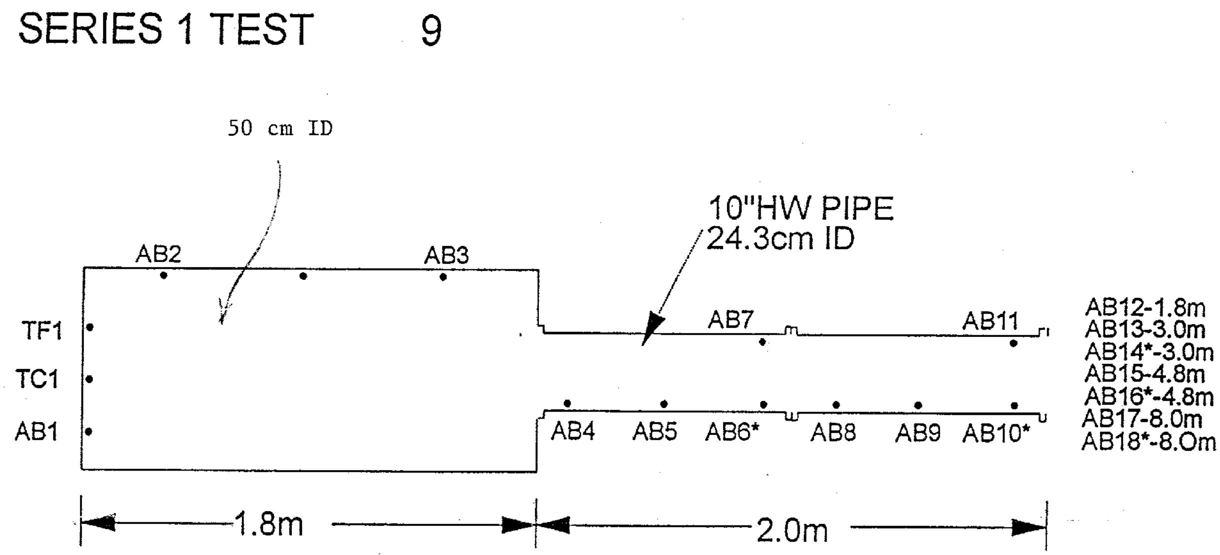

Figure 1. Small-scale shot-gun magazine model; Series 1, Test 9 layout, chamber loading density of 5.0 kg/m^3.

*STAGNATION PRESSURE

Figure 2. Comparison of measured peak overpressure from sell-scale shot-gun magazine model (Series 1, Test 9) and BLASTX3 computed data, chamber loading density of 5.0 kg/m³.

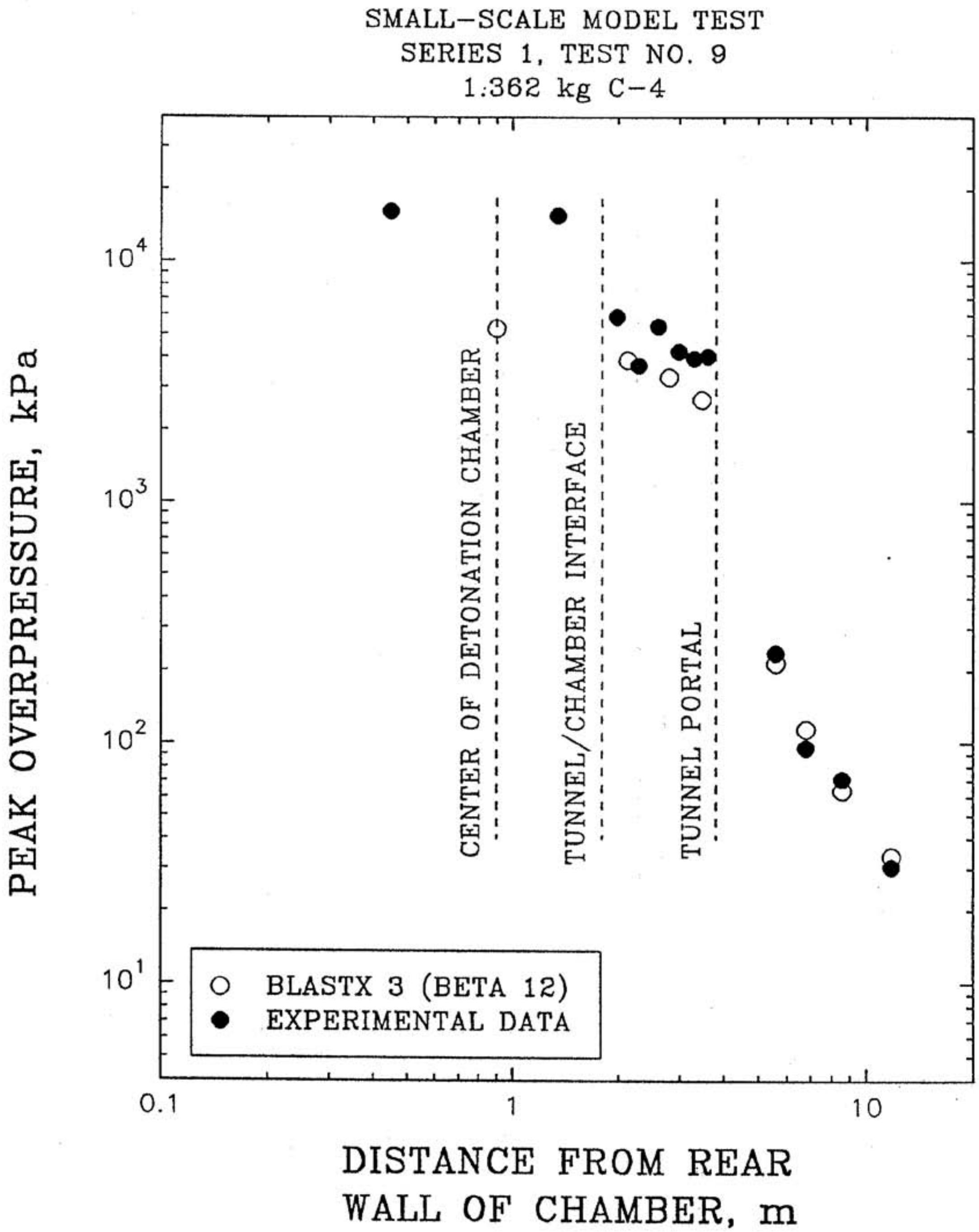

Figure 2. Comparison of measured peak overpressure from small-scale shot-gun magazine model (Series 1, Test 9) and BLASTX3 computed data, chamber loading density of 5.0 kg/m³.

Figure 3. Small-scale shot-gun magazine model; Series 1, Test 21 layout, chamber loading density of 5.0 kg/m³.

SERIES 1 TEST 21

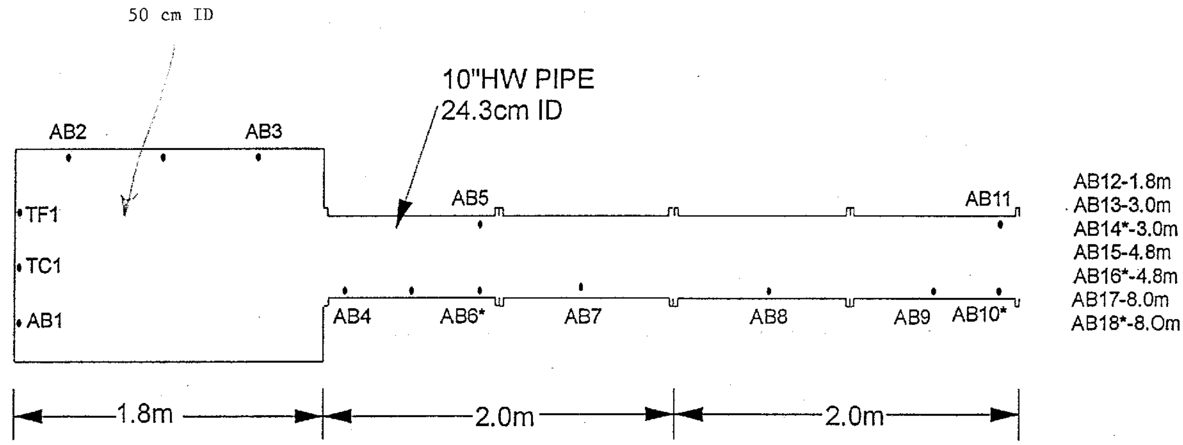

Figure 3. Small-scale shot-gun magazine model; Series 1, Test 21 layout, chamber loading density of 5.0 kg/m³.

*STAGNATION PRESSURE

Figure 4. Comparison of measured peak overpressure from small-scale shot-gun magazine model (Series 1, Test 21) and BLASTX3 computed data, chamber loading density of 5.0 kg/m³.

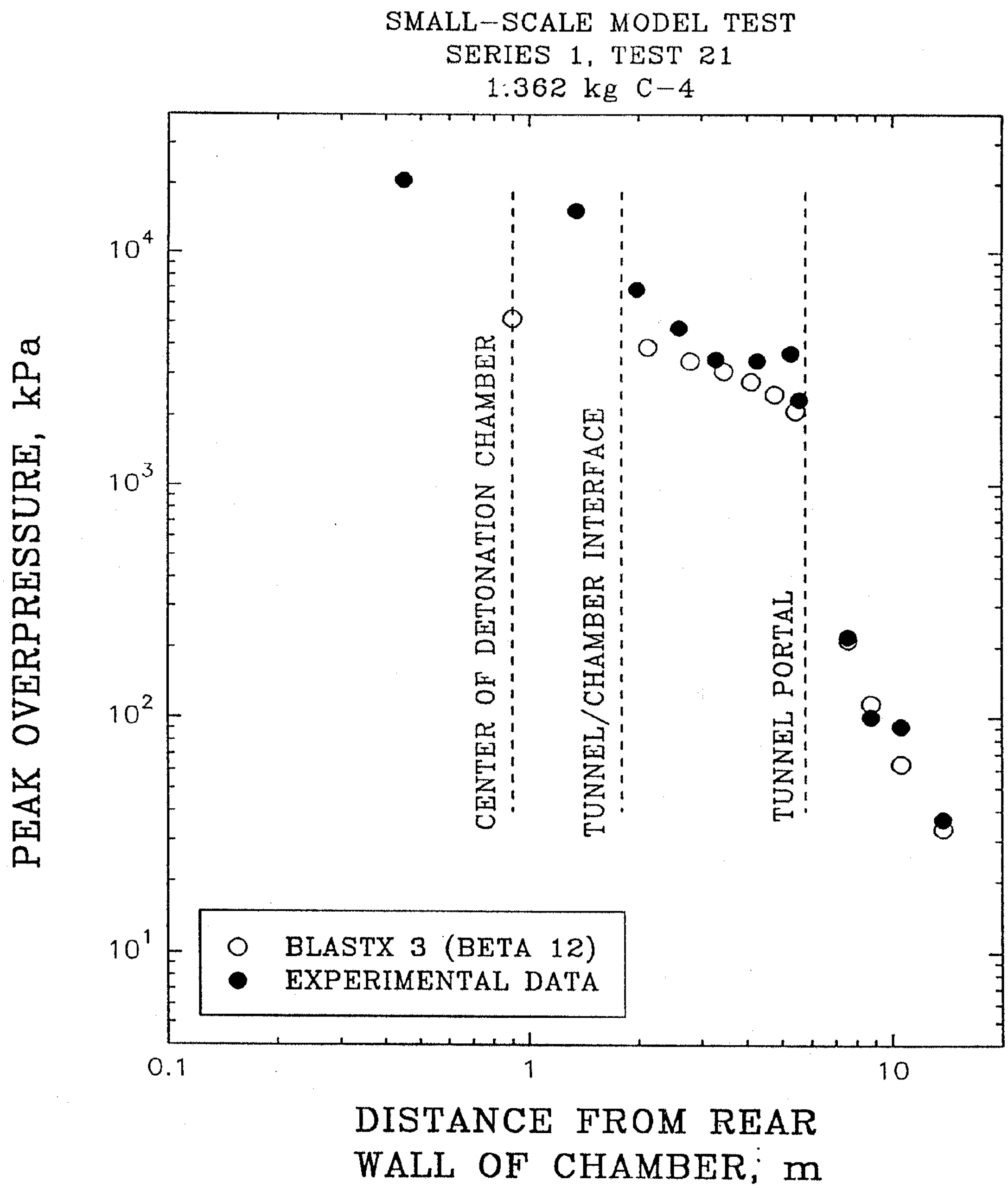

Figure 4. Comparison of measured peak overpressure from small-scale shot-gun magazine model (Series 1, Test 21) and BLASTX3 computed data, chamber loading density of 5.0 kg/m³.

F'igure 5. Small-scale magazine model with in-line expansion chamber; Series 2, layout for Tests 73, 74, and 75, chamber loading densities are 1.67, 3.33, and 5.00 kg/m^3, respectively.

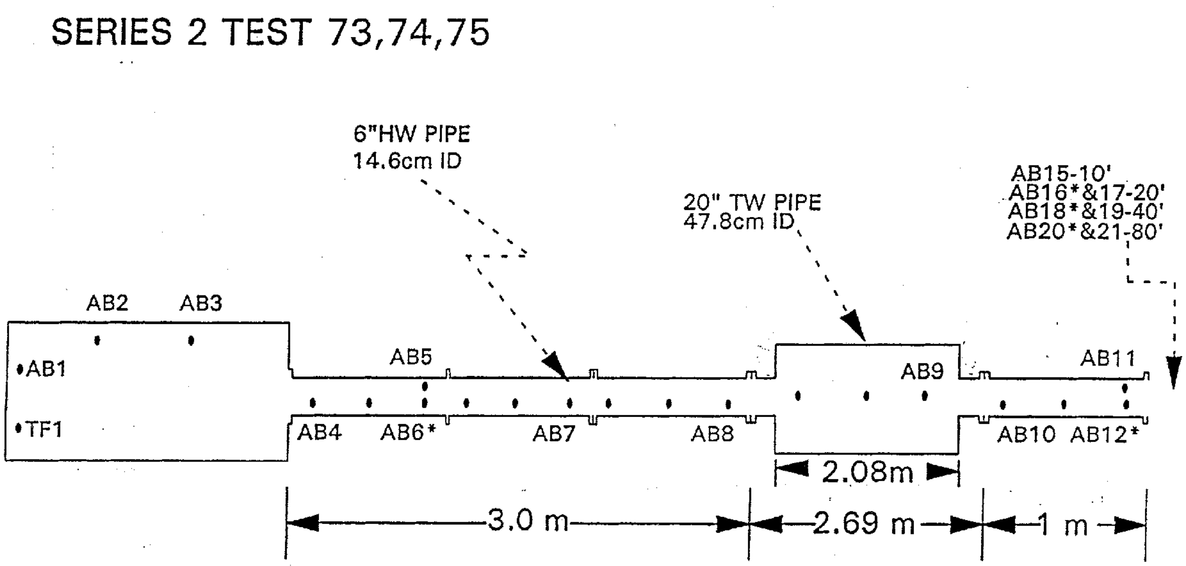

Figure 5. Small-scale magazine model with in-line expansion chamber; Series 2, layout for Tests 73, 74, and 75, chamber loading densities are 1.67, 3.33, and 5.00 kg/m^3, respectively.

STAGNATION PRESSURE *

Figure 6. Comparison of measured peak overpressure from small-scale magazine model with in-line expansion chamber (Series 2, Test 73) and BLASTX3 computed data, chamber loading density of 1,67 kg/m³.

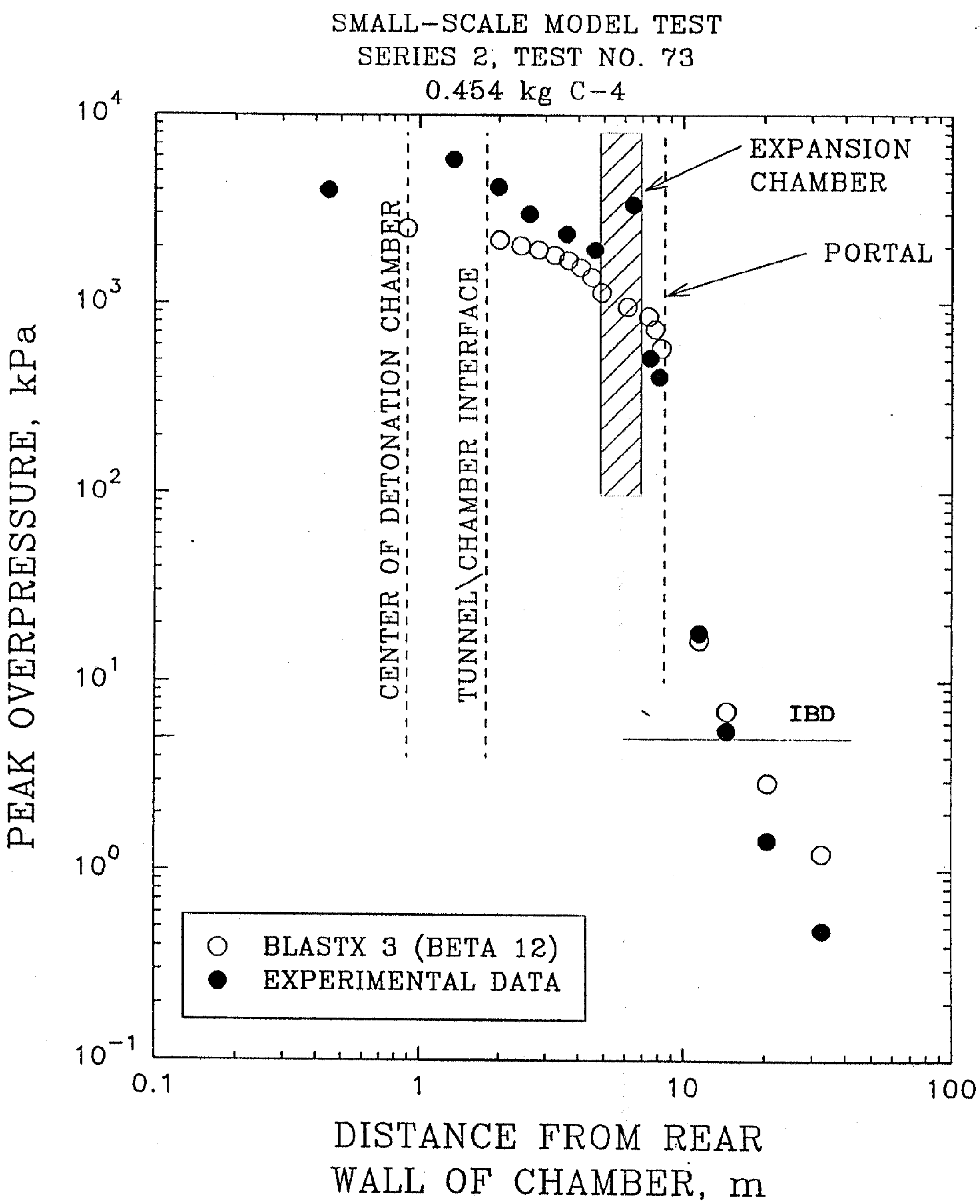

Figure 6. Comparison of measured peak overpressure from small-scale magazine model with in-line expansion chamber (Series 2, Test 73) and BLASTX3 computed data, chamber loading density of 1.67 kg/m³.

Figure 7. Comparison of measured peak overpressure from small-scale magazine model with in-line expansion chamber (Series 2, Test 74) and BIASTX3 computed data, chamber loading density of 3.33 kg/m³.

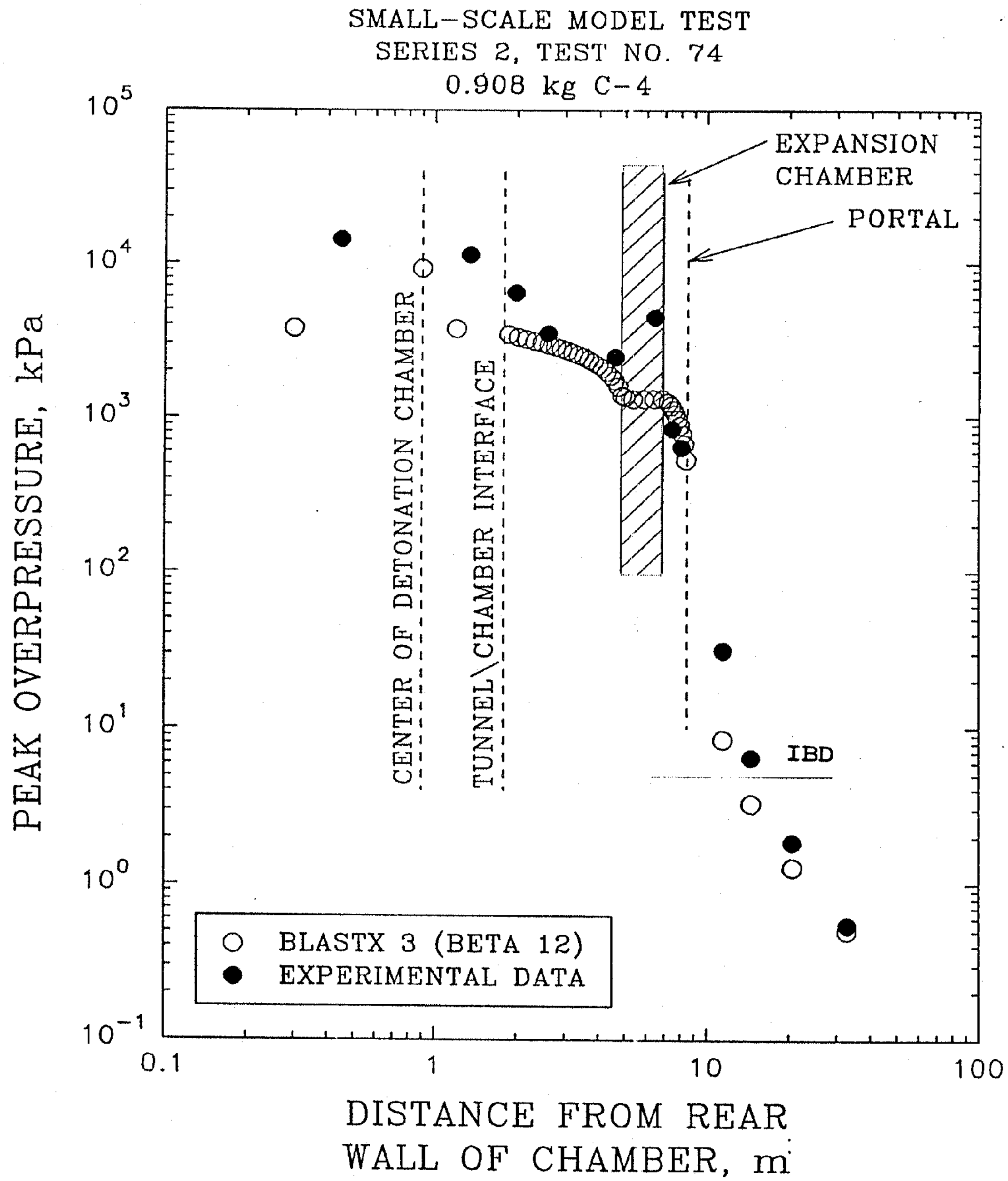

Figure 7. Comparison of measured peak overpressure from small-scale magazine model with in-line expansion chamber (Series 2, Test 74) and BLASTX3 computed data, chamber loading density of 3.33 kg/m³.

Figure 8. Comparison of measured peak overpressure from small scale magazine model with in-line expansion chamber (Series 2, Test 75) and BLASTX3 computed data, chamber loading density of 5.00 kg/m³.

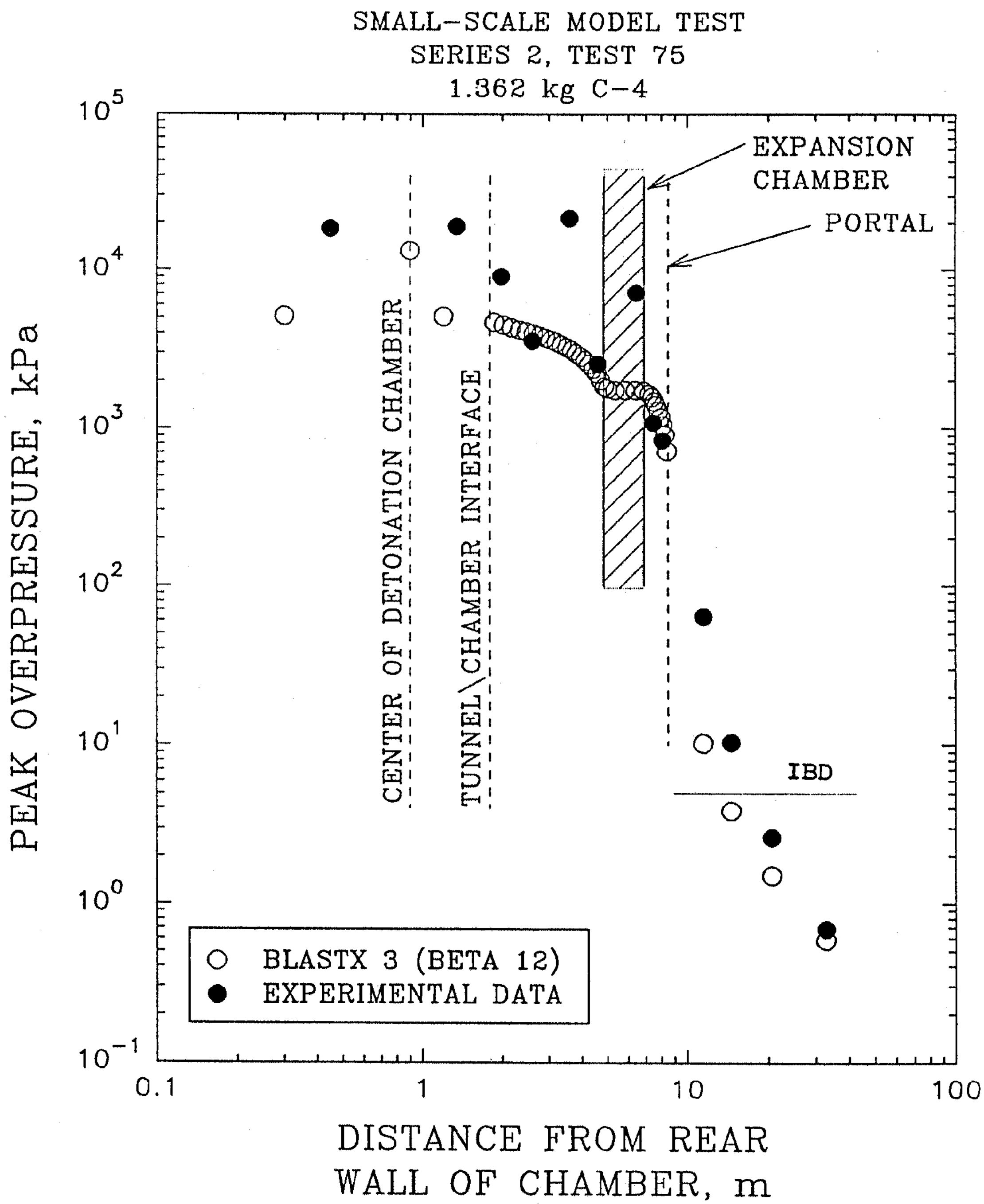

Figure 8. Comparison of measured peak overpressure from small-scale magazine model with in-line expansion chamber (Series 2, Test 75) and BLASTX3 computed data, chamber loading density of 5.00 kg/m³.

Figure 9. Small-scale magazine model with a transverse dual exit expansion chamber; Series 2, Test 82 layout, chamber loading density of 5.00 kg/m³.

SERIES 2 TEST 82

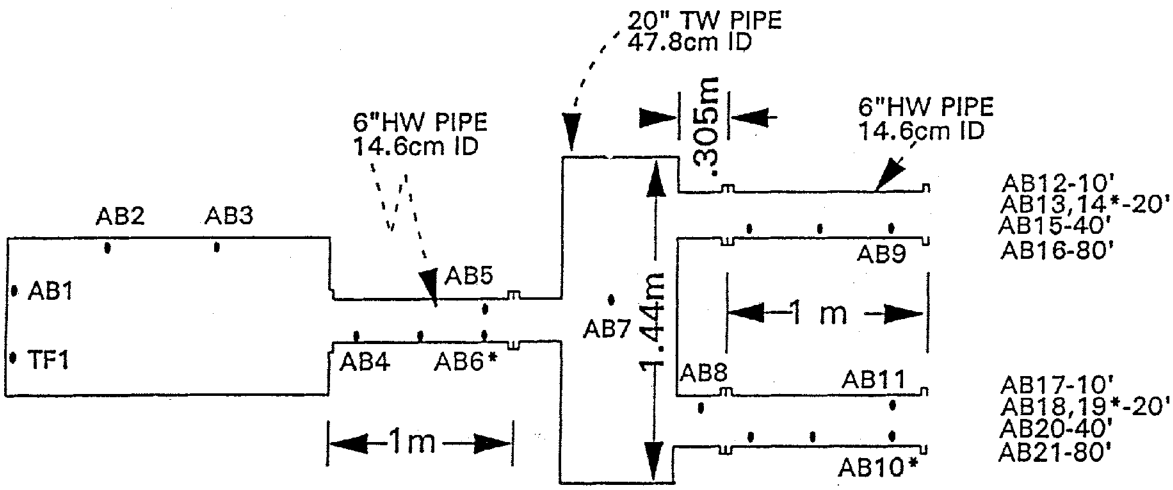

Figure 9. Small-scale magazine model with a transverse dual exit expansion chamber; Series 2, Test 82 layout, chamber loading density of 5.00 kg/m³.

STAGNATION PRESSURE *

Figure 10. Comparison of measured peak overpressure from small scale magazine model with transverse dual exit expansion chamber (Series 2, Test 82) and BLASTX3 computed data, chamber loading density of 5.00 kg/m³.

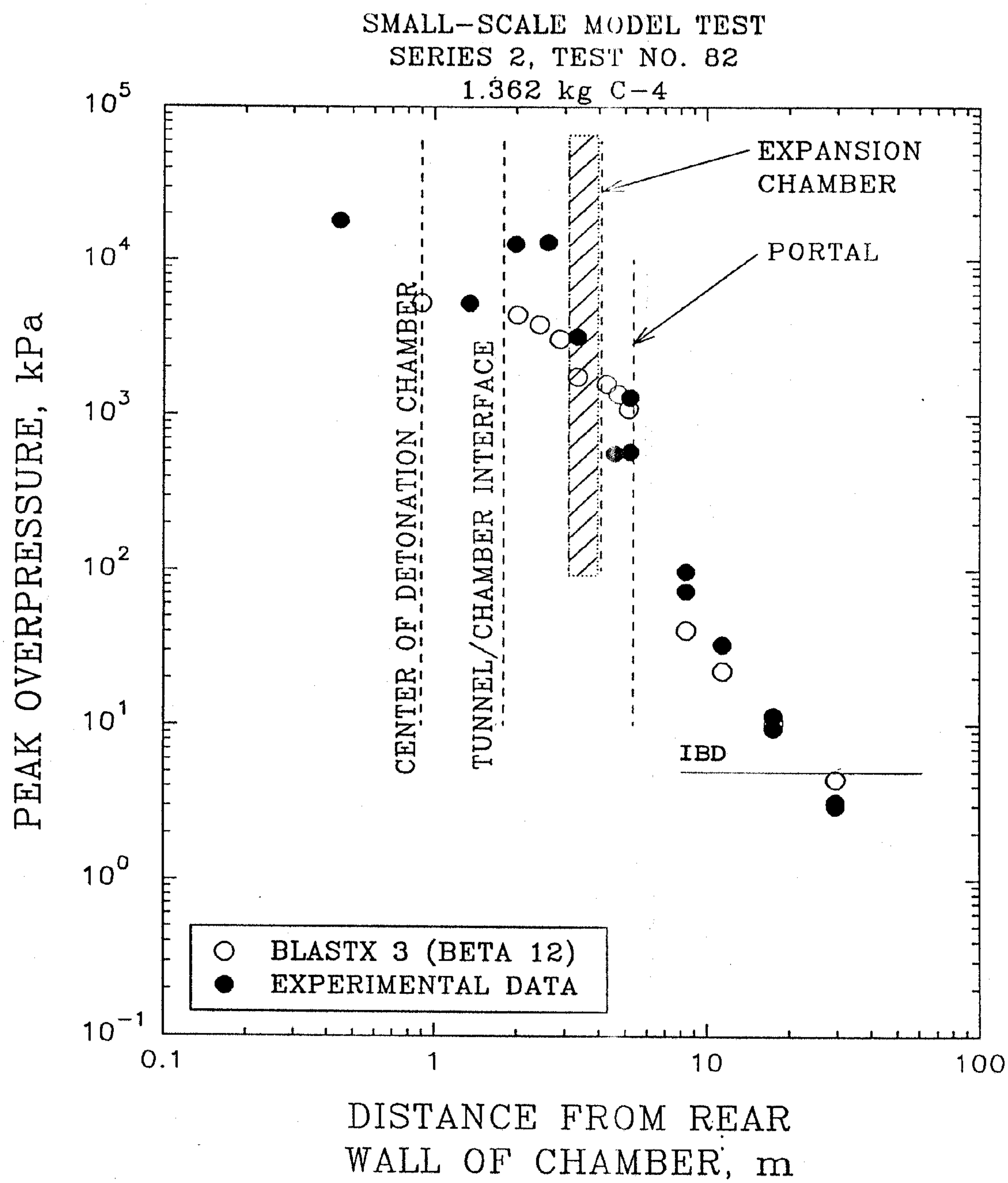

Figure 10. Comparison of measured peak overpressure from small-scale magazine model with transverse dual exit expansion chamber (Series 2, Test 82) and BLASTX3 computed data, chamber loading density of 5.00 kg/m³.

Figure 11. Small-scale shot-gun magazine model with constriction; Series 2, Test 106 layout, chamber loading density of 5.0 kg/m³.

SERIES 2 TEST 106

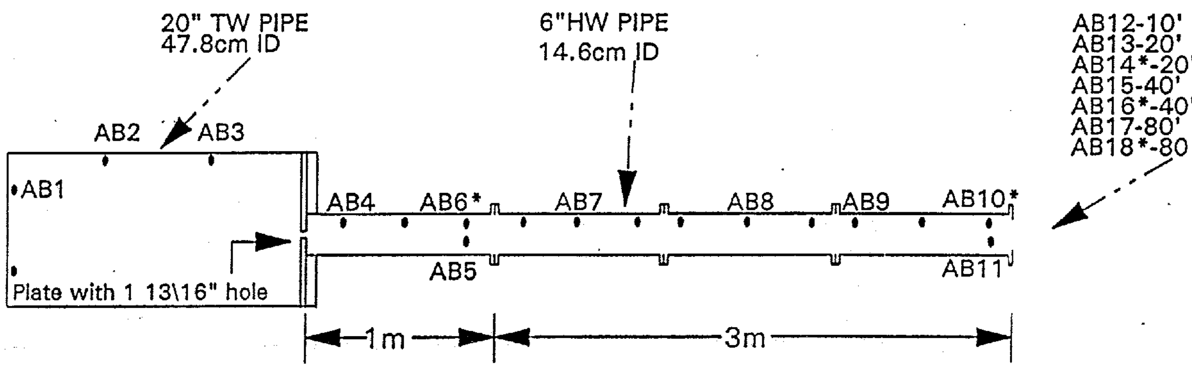

Figure 11. Small-scale shot-gun magazine model with constriction; Series 2, Test 106 layout, chamber loading density of 5.0 kg/m³.

STAGNATION PRESSURE *

Figure 12. Comparison of measured peak overpressure from small scale shot-gun magazine model with constriction (Series 2, Test 106) and BLASTX3 computed data, chamber loading density of 5.0 kg/m³.

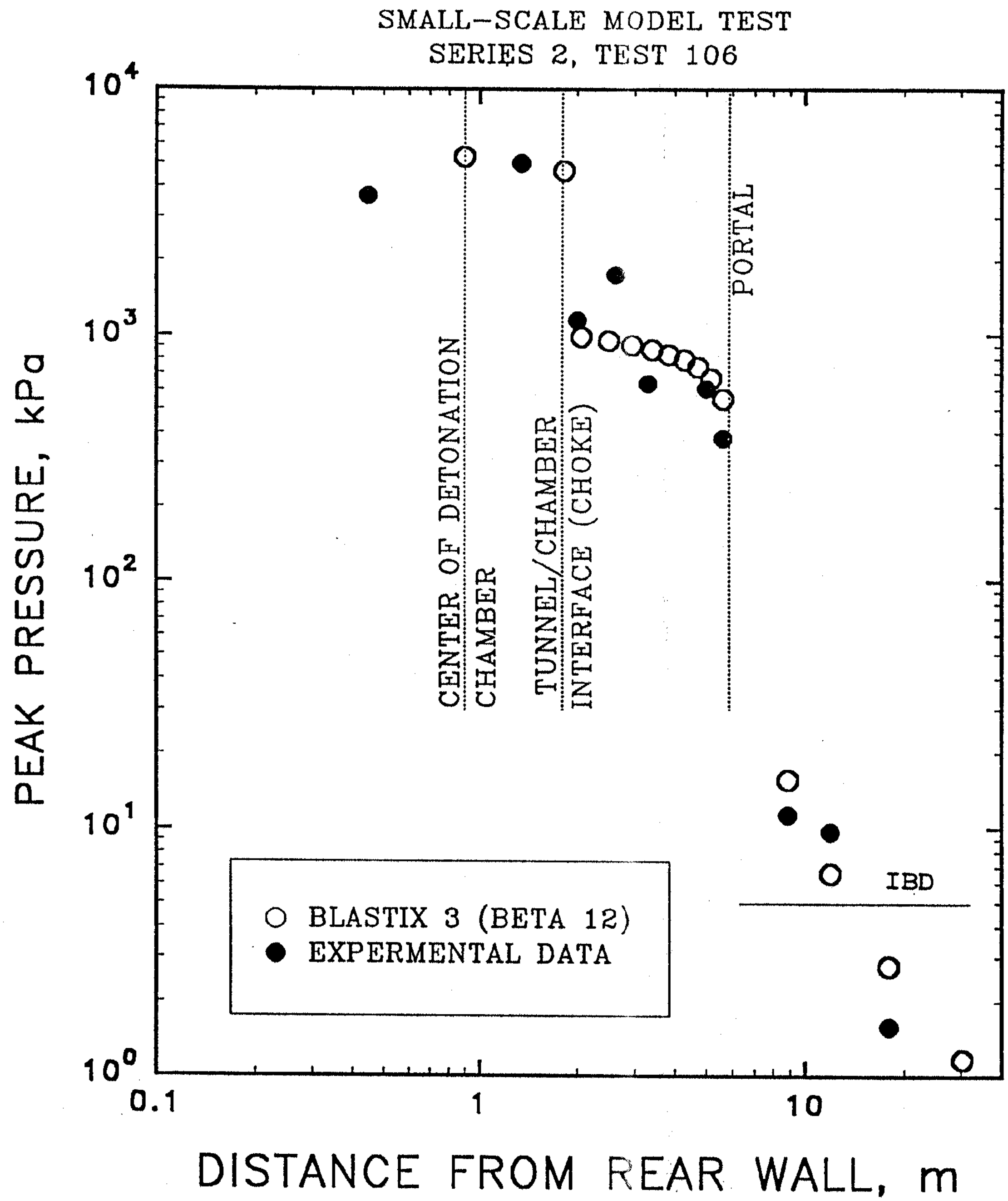

Figure 12. Comparison of measured peak overpressure from small-scale shot-gun magazine model with constriction (Series 2, Test 106) and BLASTX3 computed data, chamber loading density of 5.0 kg/m³.

Figure 13. Small-scale magazine model with dual exits (opposing ; Series 2, Test 113 layout, chamber loading density of 15.0 kg/m³.

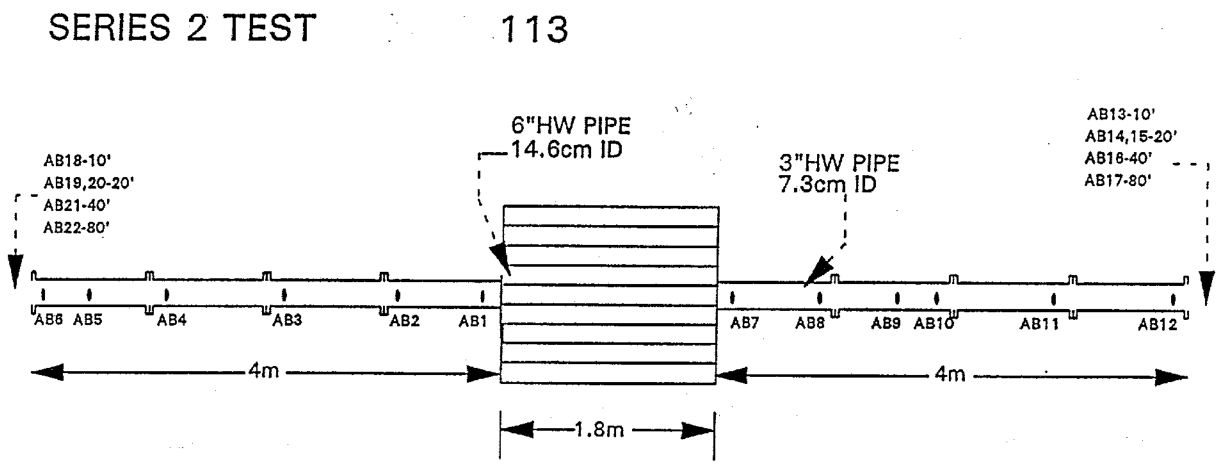

Figure 13. Small-scale magazine model with dual exits (opposing) ; Series 2, Test 113 layout, chamber loading density of 15.0 kg/m³.

Figure 14. Comparison of measured peak overpressure from small scale magazine model with dual exits (opposing) (Series 2, Test 113)-and BIASTX3 computed data, chamber loading density of 15.0 kg/m³.

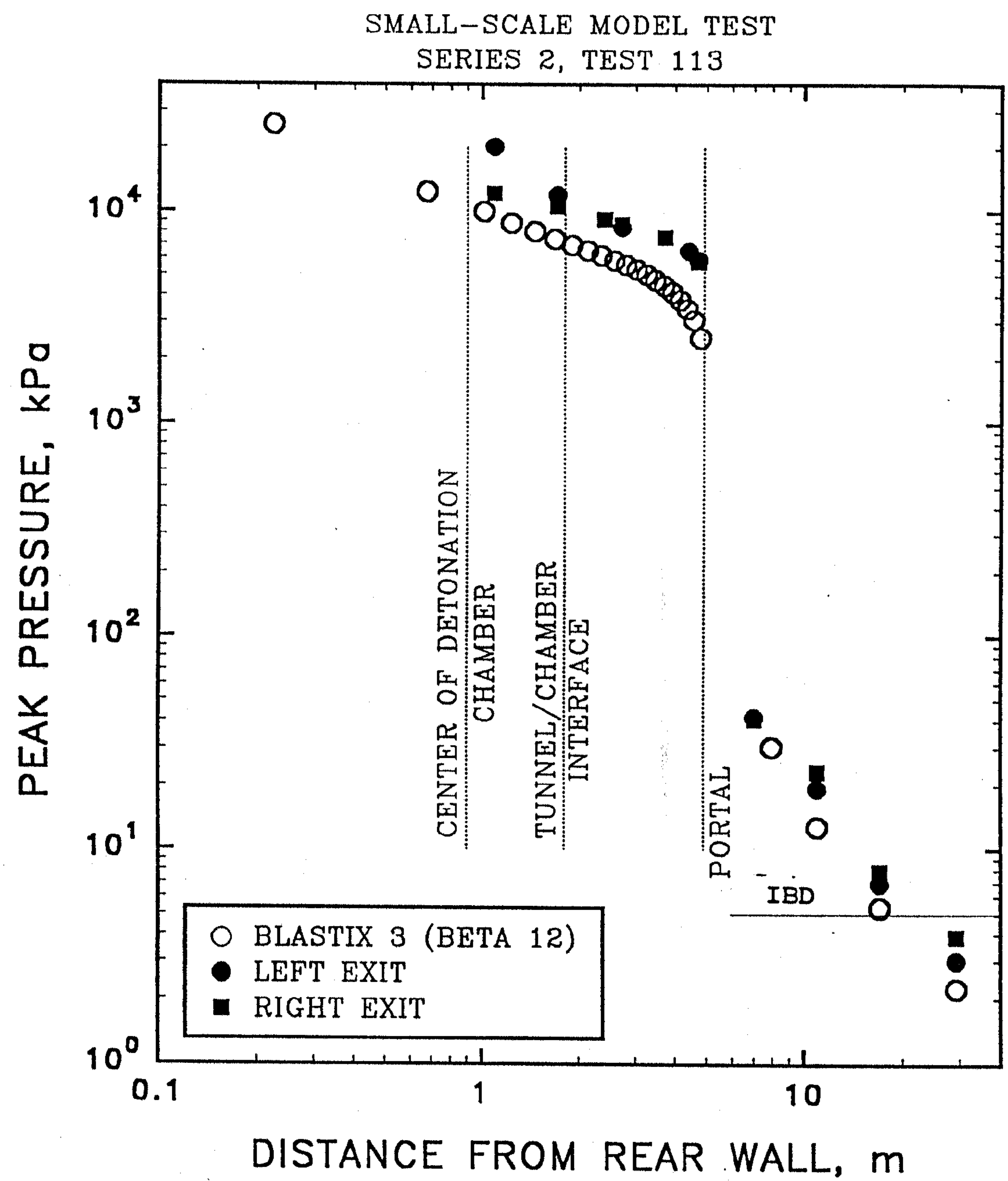

Figure 14. Comparison of measured peak overpressure from small-scale magazine model with dual exits (opposing) (Series 2, Test 113) and BLASTX3 computed data, chamber loading density of 15.0 kg/m³.

Figure 15. Small-scale magazine model with dual exits with on exit closed; Series 2, Test 117 layout, chamber loading density of 15.0 kg/m³.

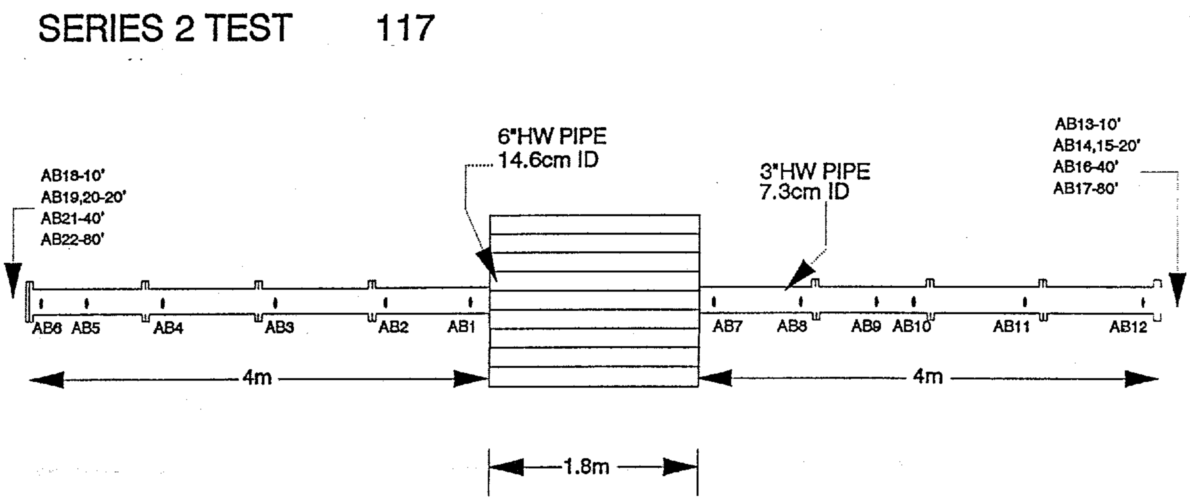

Figure 15. Small-scale magazine model with dual exits with one exit closed; Series 2, Test 117 layout, chamber loading density of 15.0 kg/m³.

Figure 16. Comparison of measured peak overpressure from small scale magazine model with dual exits with one exit closed (Series 2, Test 117) and BLASTX3 computed data, chamber loading density of 15.0 kg/m³.

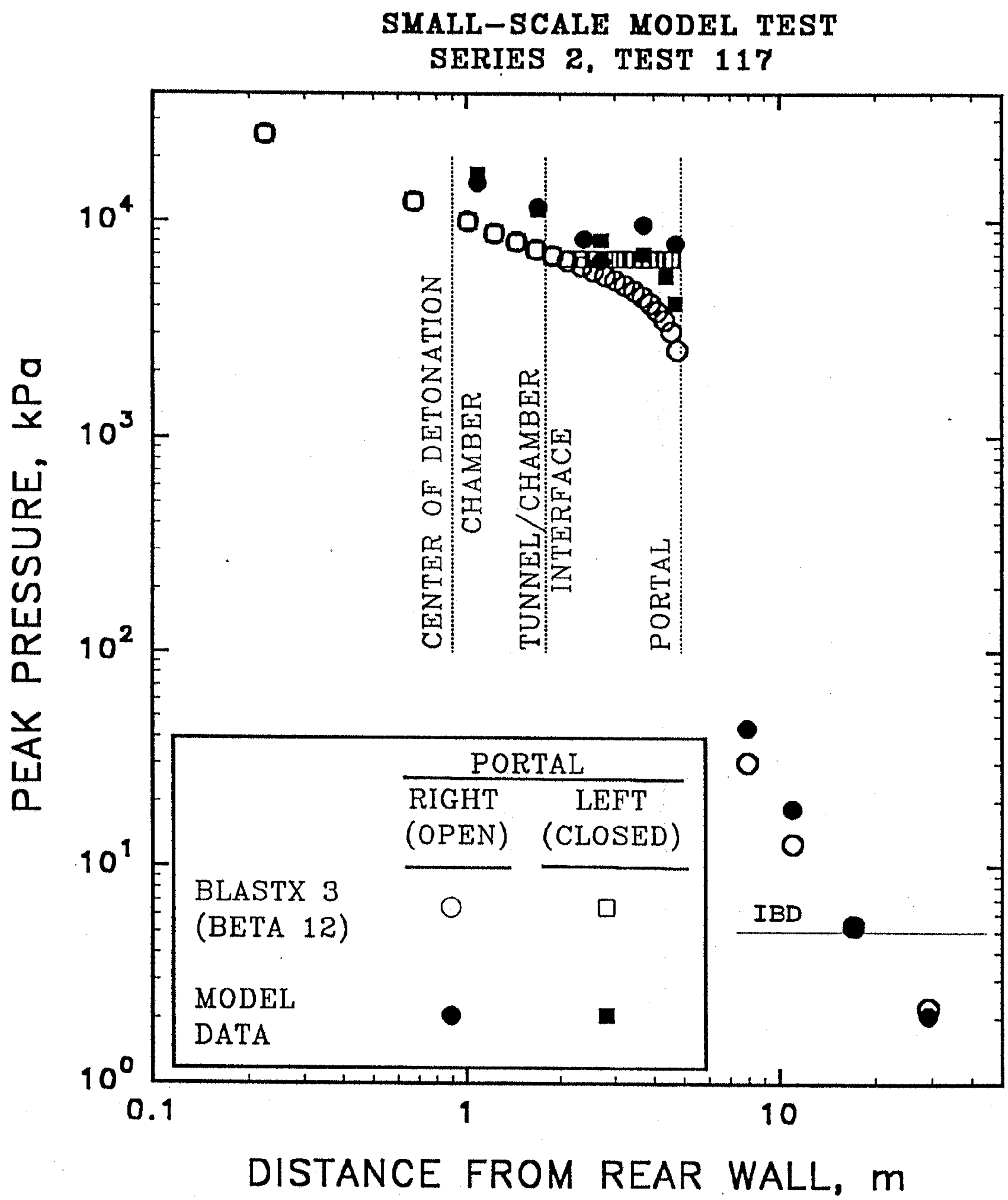

Figure 16. Comparison of measured peak overpressure from small-scale magazine model with dual exits with one exit closed (Series 2, Test 117) and BLASTX3 computed data, chamber loading density of 15.0 kg/m³.

Figure 17. Large-scale shallow underground magazine test; KLOTZ 1988 test layout at China Lake, chamber loading density of 66.4 kg/m^3.

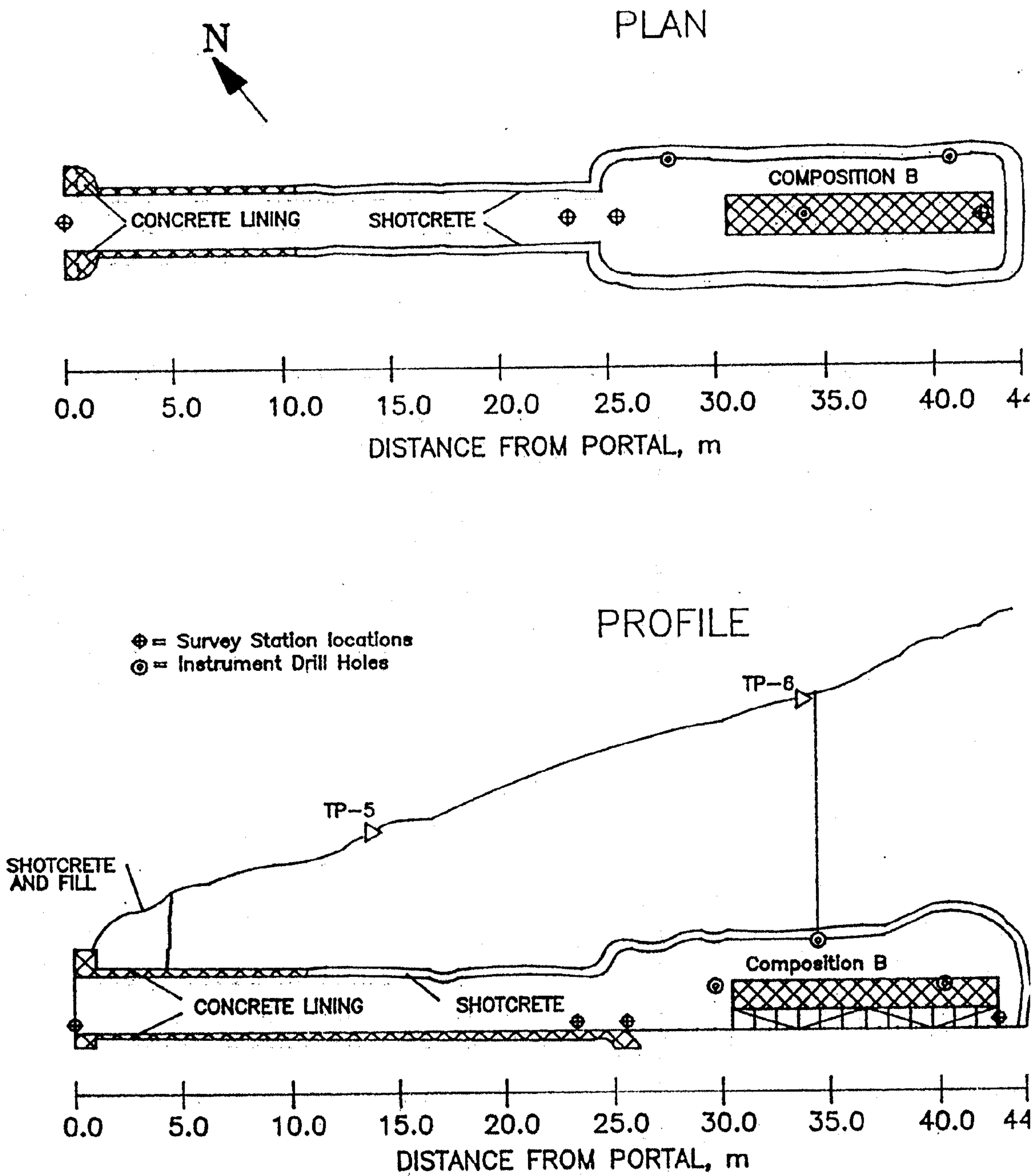

Figure 17. Large-scale shallow underground magazine test; KLOTZ 1988 test layout at China Lake, chamber loading density of 66.4 kg/m^3.

Figure 18. Comparison of measured peak overpressure from large-scale shallow underground magazine test, KLOTZ 1988 test layout at China Lake, and BLASTX3 computed data, chamber loading density of 66.4 kg/m³.

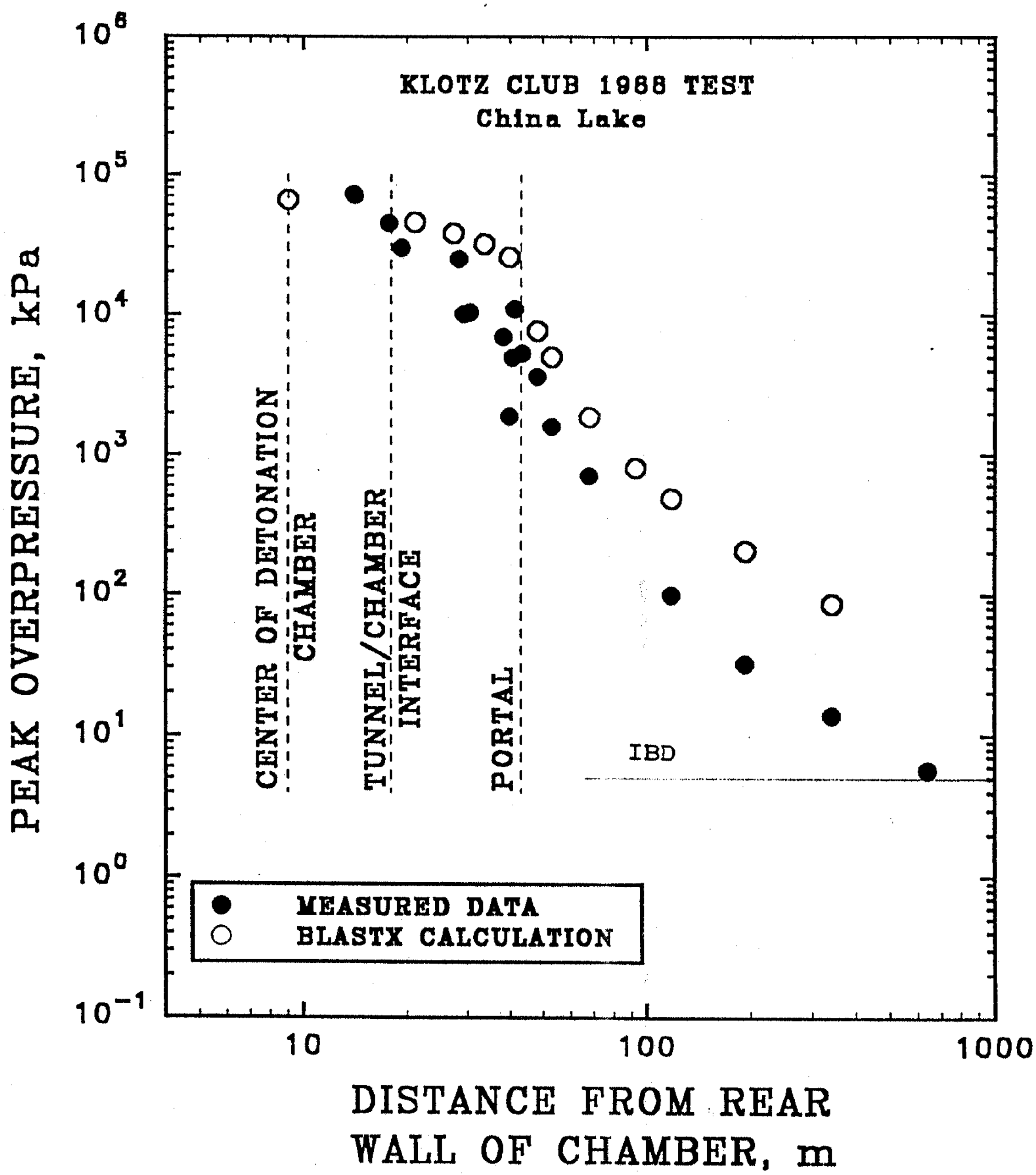

Figure 18. Comparison of measured peak overpressure from large-scale shallow underground magazine test, KLOTZ 1988 test layout at China Lake, and BLASTX3 computed data, chamber loading density of 66.4 kg/m³.

Figure 19.
Longitudinal tunnel cross-section (plan and profile), One-Third Scale Camp Stanley Underground Munitions Storage Facility, Concept Validation Tests, chamber loading density of 0.35, 1.91, and 11.1 kg/m^3, respectively.

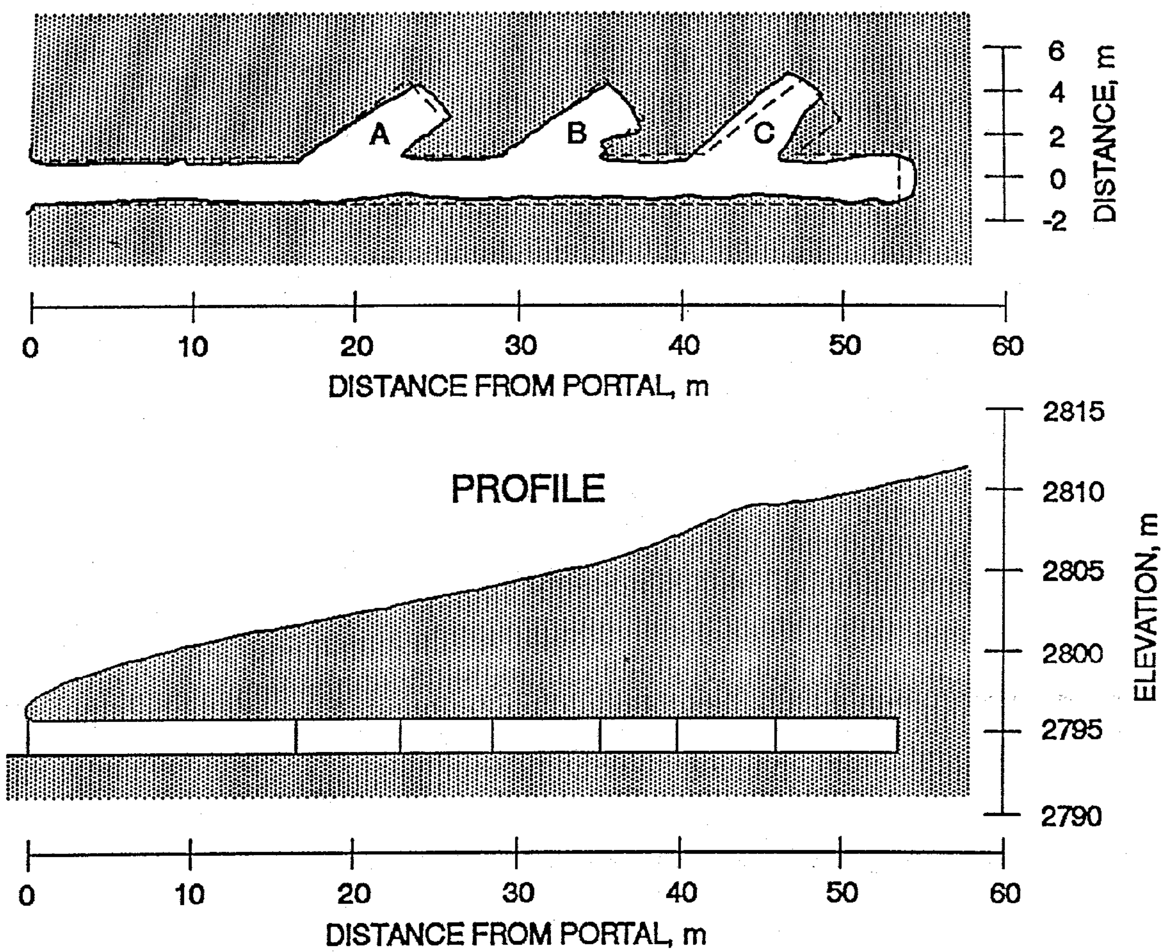

Figure 19. Longitudinal tunnel cross-section (plan and profile), One-Third Scale Camp Stanley Underground Munitions Storage Facility, Concept Validation Tests, chamber loading density of 0.35, 1.91, and 11.1 kg/m^3, respectively.

Figure 20. Comparison of measured peak overpressure from One-third scale Camp Stanley Underground Munitions Storage Facility, Concept Validation Test, test no. 1 layout, and BLASTX3 computed data, chamber loading density of 0.35 kg/m^3.

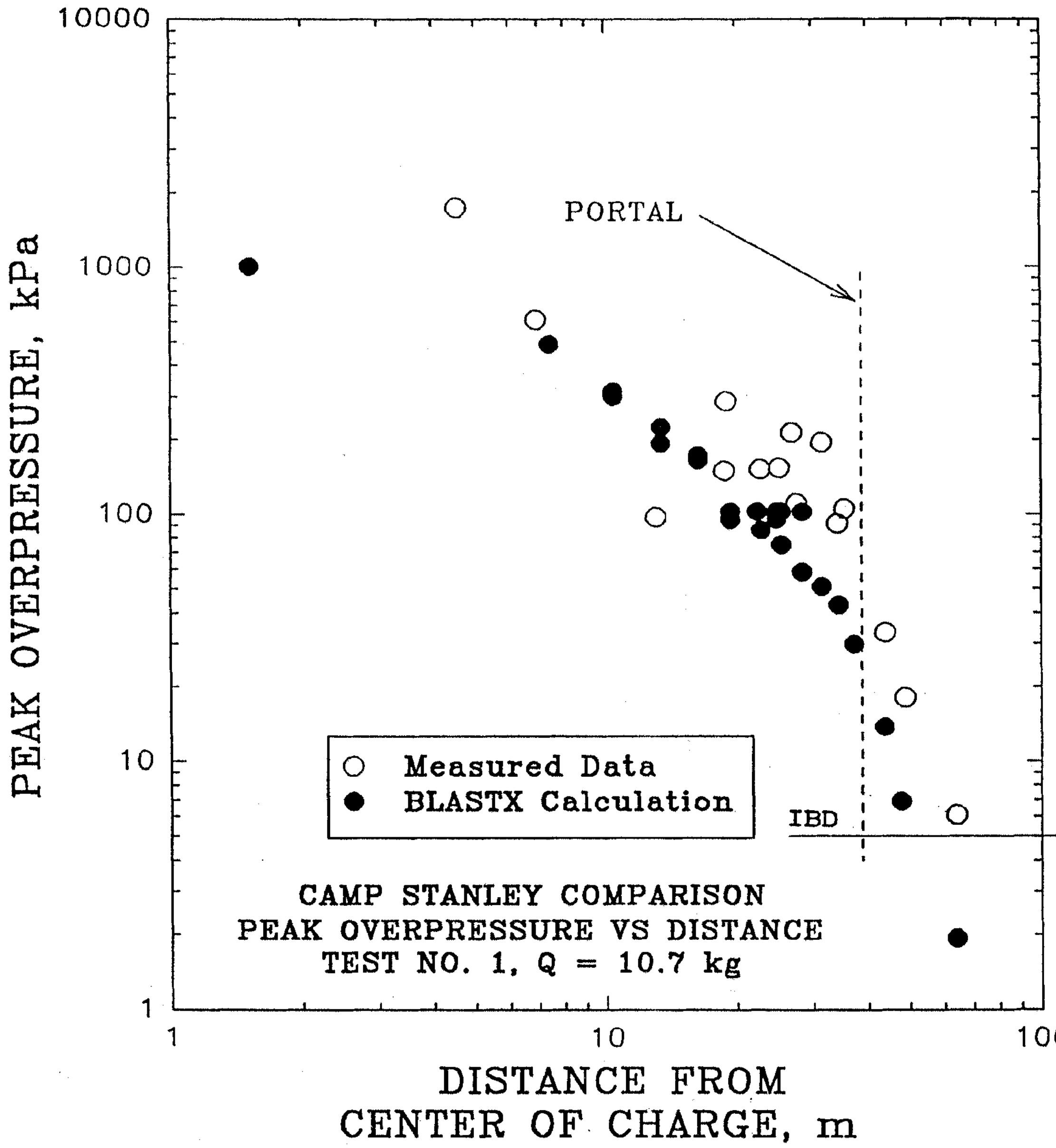

Figure 20. Comparison of measured peak overpressure from One-Third scale Camp Stanley Underground Munitions Storage Facility, Concept Validation Test, test no. 1 layout, and BLASTX3 computed data, chamber loading density of 0.35 kg/m^3.

Figure 21. Comparison of measured peak overpressure from One Third scale Camp Stanley Underground Munitions Storage Facility, Concept Validation Test, test no. 2 layout, and BLASTX3 computed data, chamber loading density of 1.91 kg/m³.

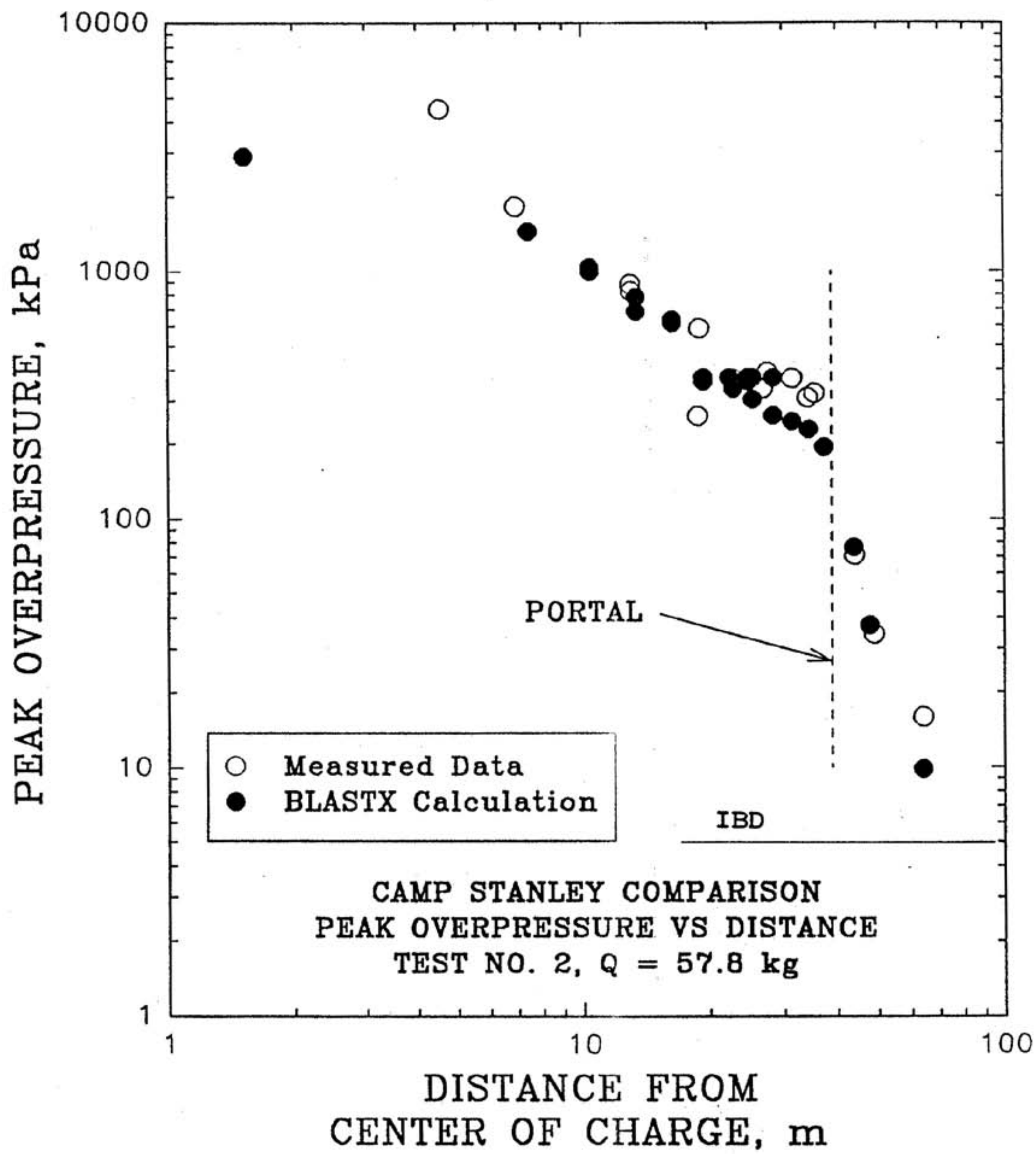

Figure 21. Comparison of measured peak overpressure from One-Third scale Camp Stanley Underground Munitions Storage Facility, Concept Validation Test, test no. 2 layout, and BLASTX3 computed data, chamber loading density of 1.91 kg/m³.

Figure 22. Comparison of measured peak overpressure from One-third scale Camp Stanley Underground Munitions Storage Facility, Concept Validation Test, test no. 4 layout, and BIASTX3 computed data, chamber loading density of 11.1 kg/m³.

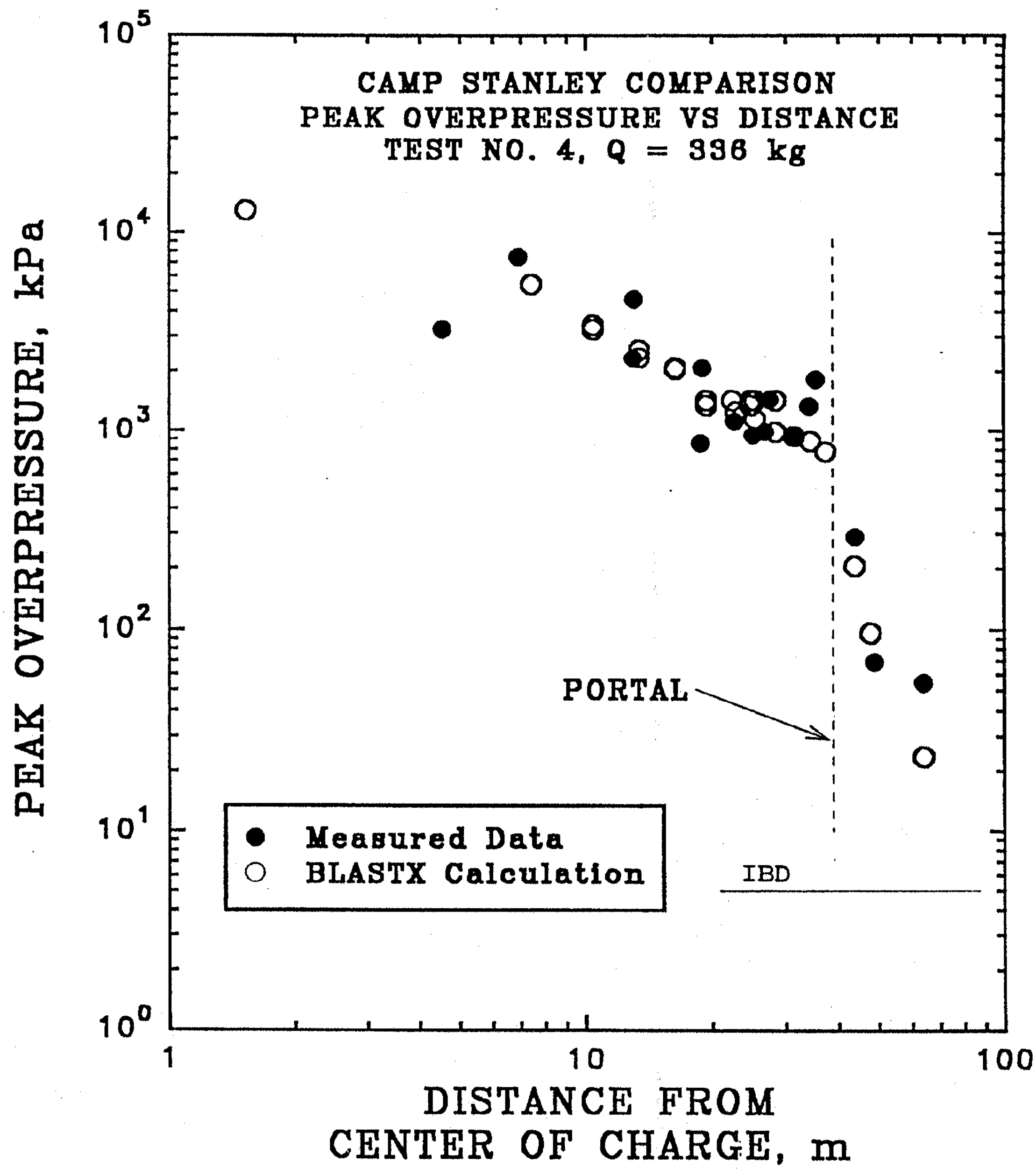

Figure 22. Comparison of measured peak overpressure from One-Third scale Camp Stanley Underground Munitions Storage Facility, Concept Validation Test, test no. 4 layout, and BLASTX3 computed data, chamber loading density of 11.1 kg/m³.

Figure 23. Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Tests in the Linchburg Mine, test layout, Chamber No. 4 loading densities of 1.1-5.5, 14.6, and 37.3 kg/m^3.

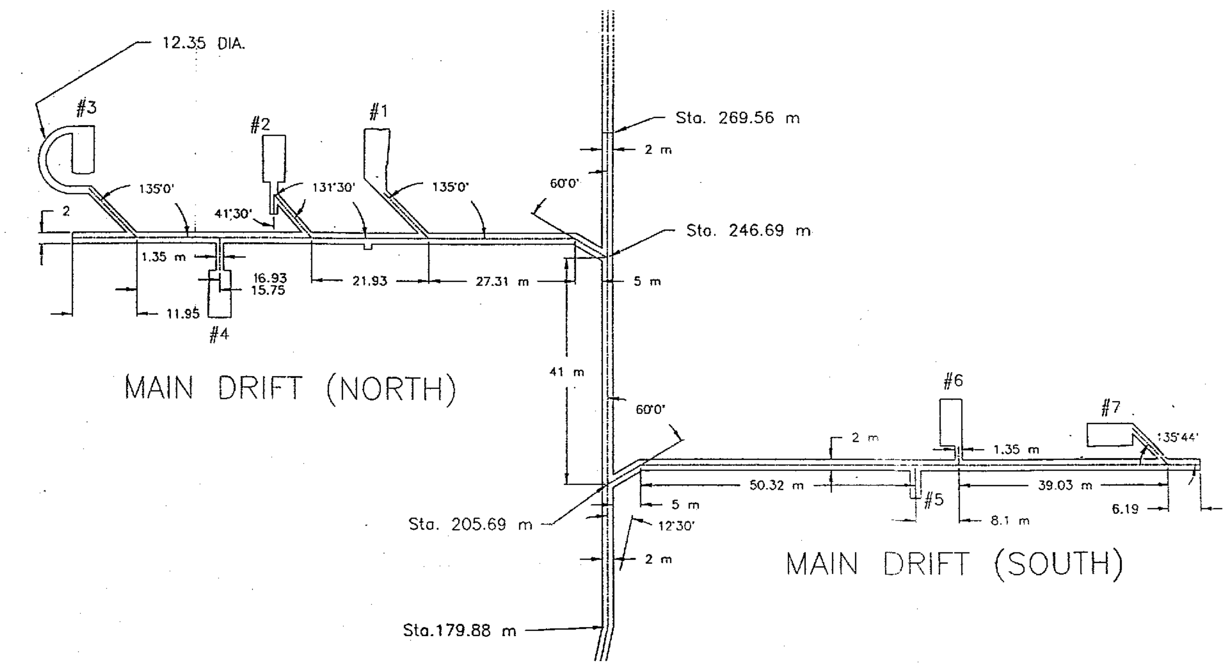

Figure 23. Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Tests in the Linchburg Mine, test layout, Chamber No. 4 loading densities of 1.1, 5.5, 14.6, and 37.3 kg/m^3.

Figure 24. Comparison of measured peak overpressure from Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Test No. 2, and BLASTX3 computed data, Chamber No. 4 loading density of 1.1 kg/m^3.

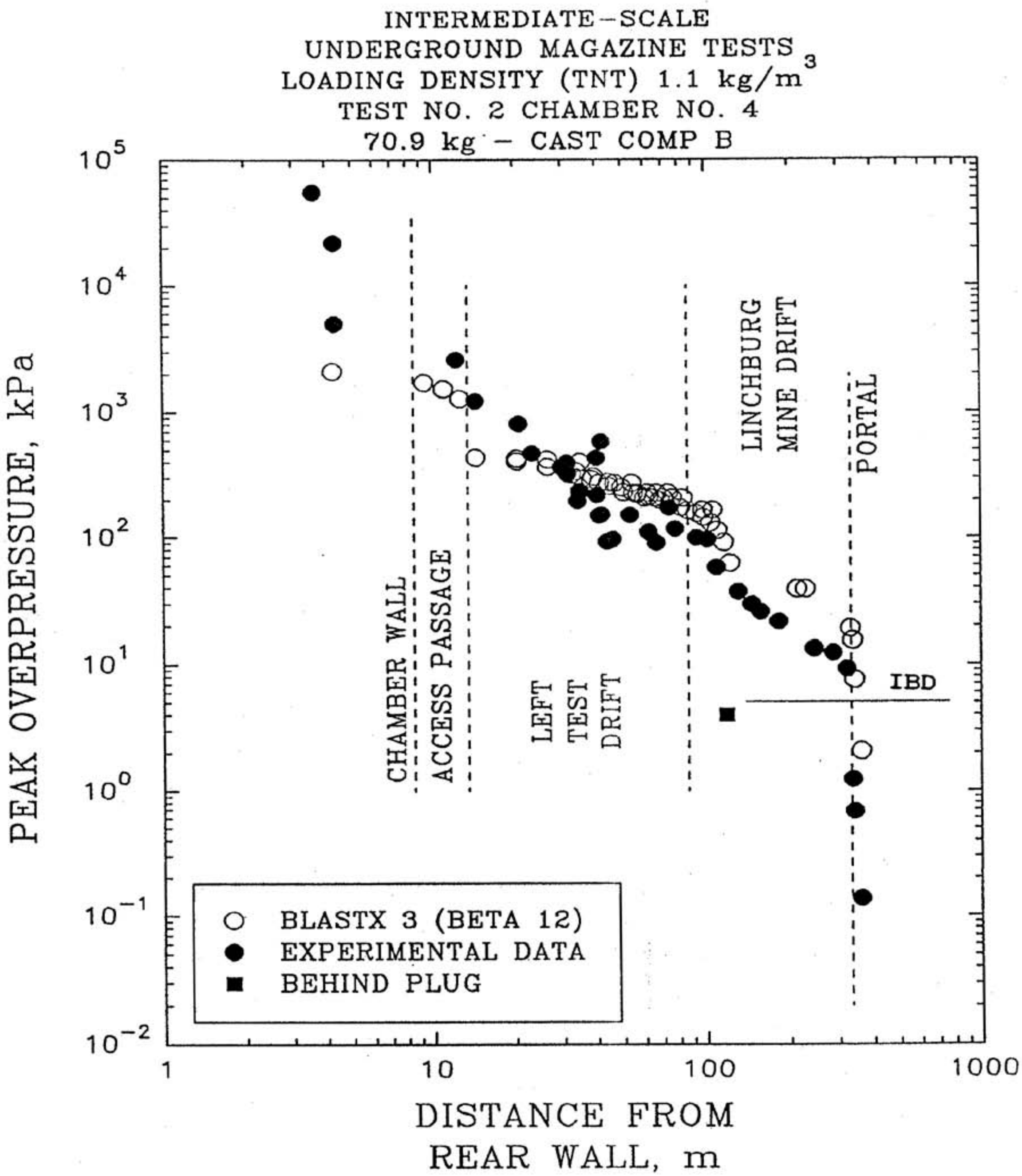

Figure 24. Comparison of measured peak overpressure from Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Test No. 2, and BLASTX3 computed data, Chamber No. 4 loading density of 1.1 kg/m^3.

Figure 25. Comparison of measured peak overpressure from Joint US/ROK R&D Program Intermediate-Scale Underground Magazine Test No. 3, and BLASTX3 computed data, Chamber No. 4 loading density of 5.5 kg/m³.

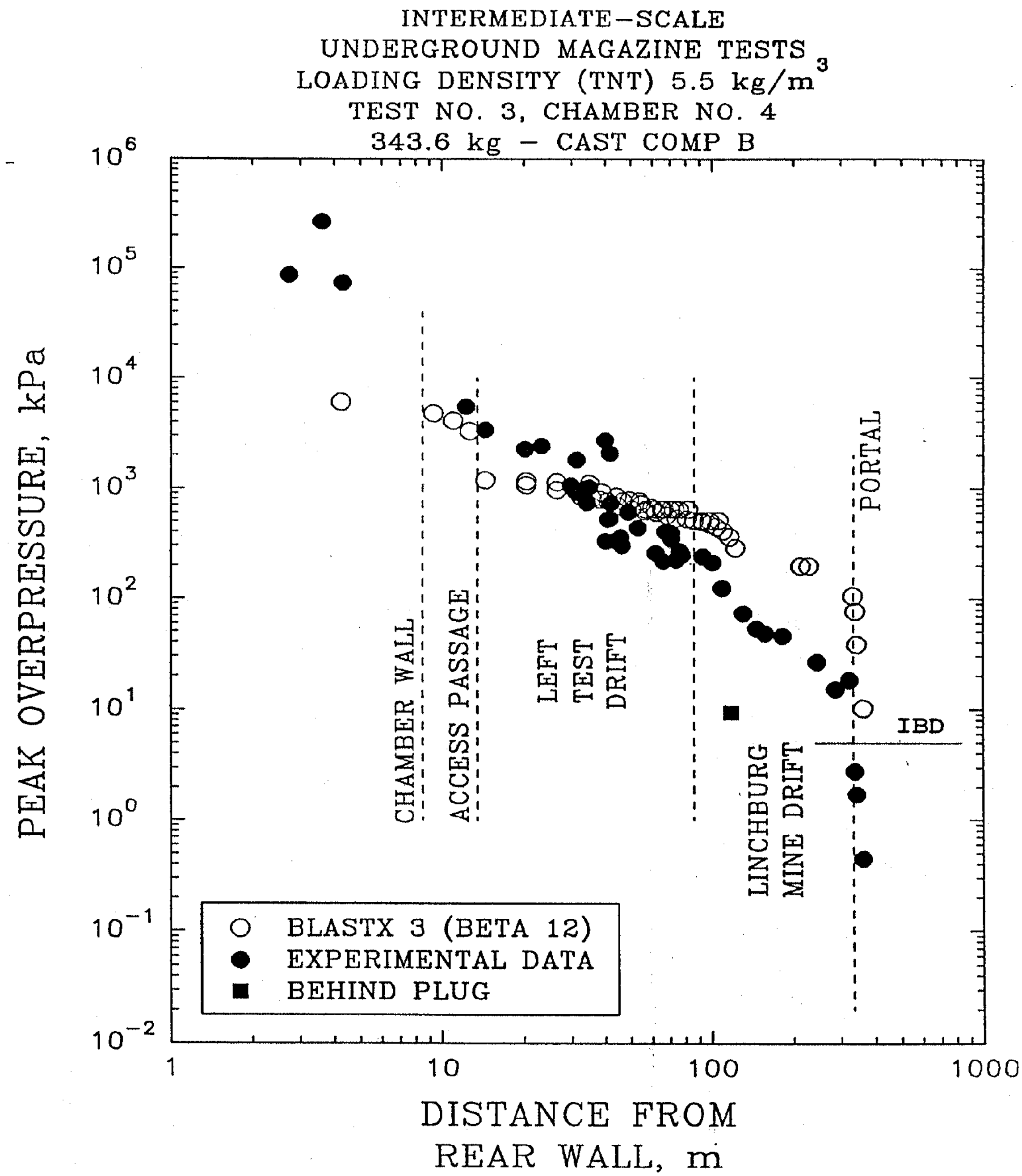

Figure 25. Comparison of measured peak overpressure from Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Test No. 3, and BLASTX3 computed data, Chamber No. 4 loading density of 5.5 kg/m³.

Figure 26. Comparison of measured peak overpressure from Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Test No. 5, and BLASTX3 computed data, Chamber No. 4 loading density of 14.6 kg/m^3.

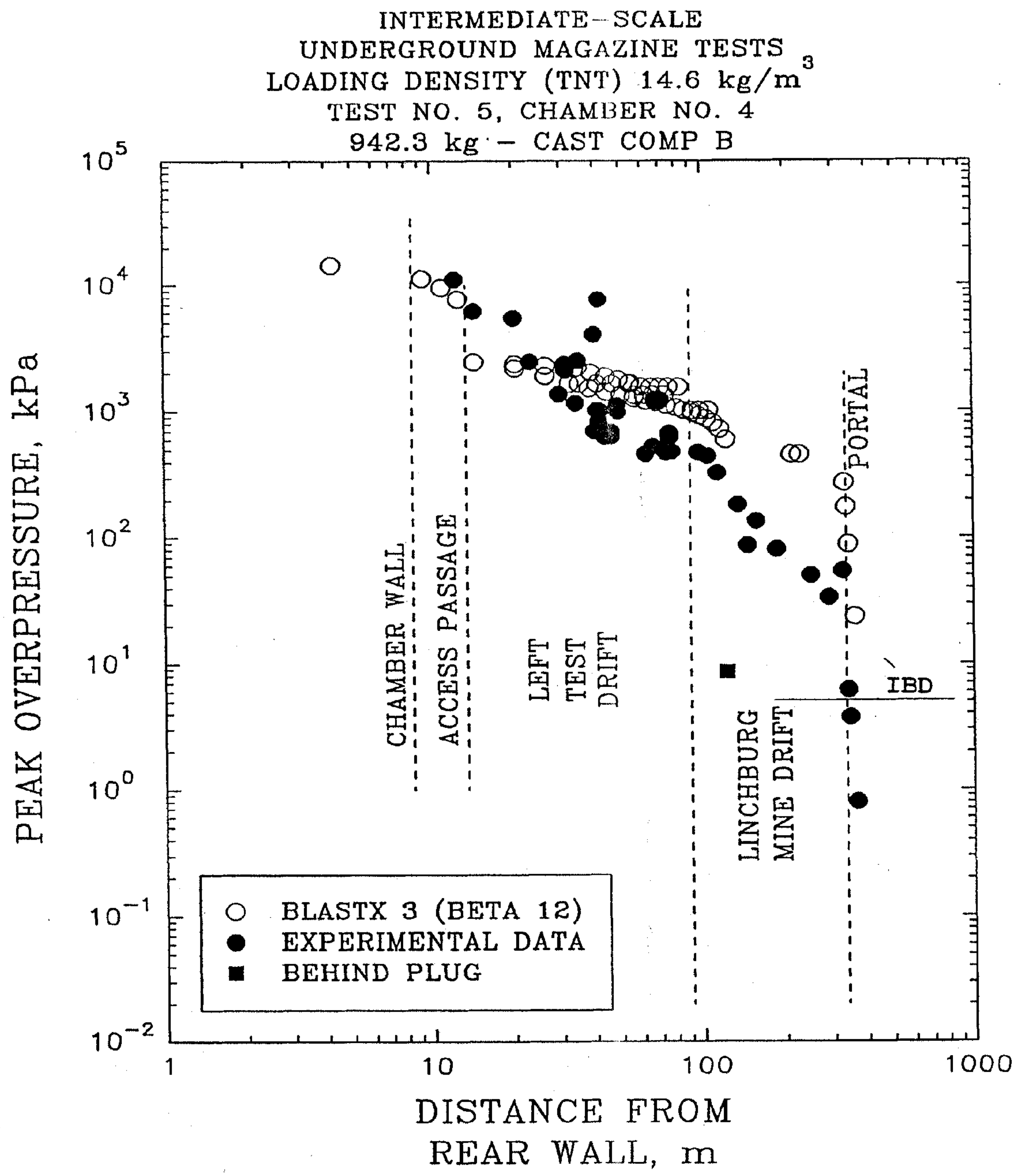

Figure 26. Comparison of measured peak overpressure from Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Test No. 5, and BLASTX3 computed data, Chamber No. 4 loading density of 14.6 kg/m^3.

Figure 27. Comparison of measured peak overpressure from Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Test No. 6, and BLASTX3 computed data, Chamber No. 4 loading density of 37.3 kg/m³.

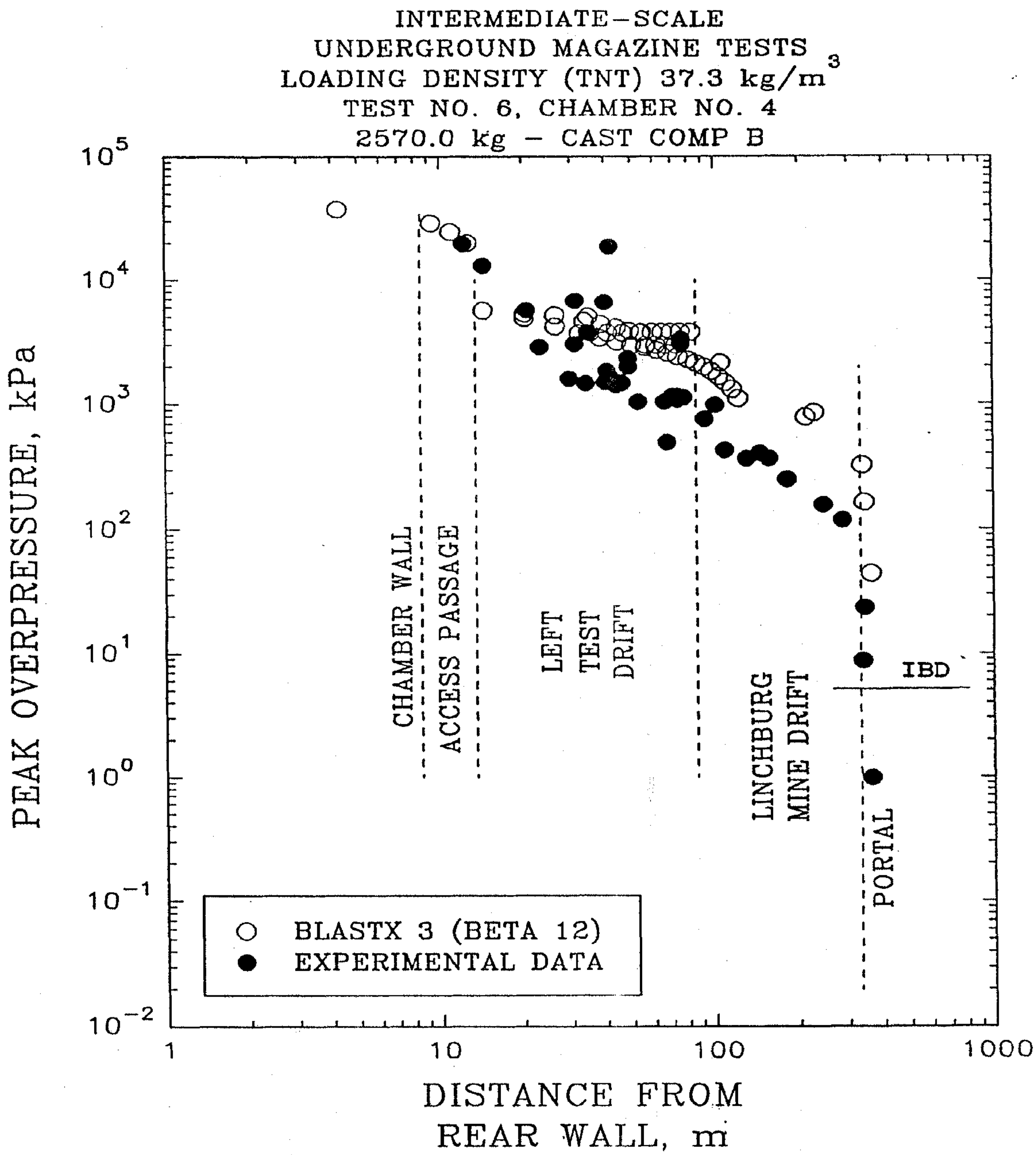

Figure 27. Comparison of measured peak overpressure from Joint US/ROK R&D Program, Intermediate-Scale Underground Magazine Test No. 6, and BLASTX3 computed data, Chamber No. 4 loading density of 37.3 kg/m³.